Recent Water Level Declines in the Lake Michigan−Huron System

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Great Lakes water levels have fluctuated over thousands of years. High water levels were a problem in the 1980s, but a recent sudden drop in Lakes Michigan and Huron has caused particular concern, in part because lower water levels are consistent with many global climate change scenarios. We examined water level data (1860–2006) representing Lakes Michigan and Huron to evaluate changes in both long-term and seasonal patterns over time, and explore relationships with candidate predictor variables. Our tools for this analysis included both Seasonal Trend decomposition using Loess (STL), and dynamic linear models (DLM). In addition to the recent decline, STL results reveal a sustained decline around 1900, a long-term periodicity of ~30 years, and an unexpected correspondence with sunspot activity. DLM results indicate a relationship with precipitation over a three-year lagged period, which has been essentially unchanging from 1900 to present. Additionally, the DLM highlights an underlying lake level decline beginning in ~1973 and continuing to the present, which may have been obscured by concurrently increasing precipitation into the 1990s. The current underlying decline might be related to a simultaneous evaporation increase, however, our model could not confirm this relationship, possibly due to the shorter period of record for evaporation data. We cannot be certain that the present observed water level drop is caused by factors related to global climate change, or that it portends a long-term problem. However, because the underlying decline has been ongoing for ~33 years it may be prudent to include lower lake levels in future management planning.

Introduction

The Laurentian Great Lakes (Figure 1) are an important resource for Canada and the United States, covering >245,000 km^2 (94,000 miles^2) and containing ~23,000 km^3 (5,400 miles^3) of water. They hold ~18% of the world's available fresh water and over 80% of the U.S. stock. The Great Lakes supply >40 million Canadian and U.S. citizens with drinking water. Thus water quality and availability are important issues for the region (*1*).

Water level fluctuations are an ongoing concern in the Great Lakes. In the 1980s−90s high lake levels were a problem, causing considerable damage to shoreline structures (*2*). More recently the issue has reversed. Low water levels are causing difficulties in Lakes Superior, Michigan, and Huron (*1*). Fluctuating water levels are not a recent phenomenon; Great Lakes levels have varied over thousands of years (*3, 4*). However, current falling water levels are worrisome because they are consistent with many climate change projections (*5–8*), raising concern that the low levels may be sustained.

The estimated cost resulting from continued declines is substantial (*9*). The shipping industry has been particularly affected; for every 0.0254 m (one inch) below full draft that the lakes drop ships lose ~50–270 t of capacity, depending on the size of the vessel (*10*). Since 1997 Lakes Michigan and Huron have fallen ~1.1 m causing ships to light load and resulting in more trips for the same amount of cargo. Lakefront property-owners and lakeside businesses have also been adversely affected as the waterfront has receded, limiting access from piers and docks. Additionally, shallower water in nearshore areas and embayments such as Saginaw Bay is believed to be exacerbating a resurgence of nuisance and harmful algal conditions resulting from the concurrent invasion of dreissenid mussels (*11*).

Lakes Michigan and Huron are connected by the Straits of Mackinac and behave hydraulically as one lake. Additionally, Michigan and Huron are not regulated for hydropower or commercial navigation and are only minimally influenced by regulation of the other lakes (*12*). Therefore, water levels in the Michigan−Huron system are largely responding to climatic or other large-scale forces and the data from these lakes provide clues regarding how these drivers are changing. Our analysis is based on data from 1860 to 2006 representing water levels in Lakes Michigan and Huron and considers precipitation, evaporation, and runoff data covering shorter, more recent periods of record. Other factors such as snowmelt and ice cover may be important factors in the Michigan−Huron water balance, but are only implicitly considered to the extent that they influence precipitation and evaporation. Additionally, because initial exploration suggested a relationship between water level and sunspot periodicity, we included sunspot number in our analysis.

Methods

Data. Water level data for Lakes Michigan−Huron (1860–2006) were obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Ocean Services database (*13*) for the reference gage at Harbor Beach. NOAA's Geodetic Survey computes an International Great Lakes Datum (IGLD) every 25 years to account for isostatic rebound; presently, all the Great Lakes are referenced to IGLD85. Monthly precipitation (1900–2004), runoff, and evaporation (1948–2005) data were obtained from NOAA's Great Lakes Environmental Research Laboratory's Hydrologic Database (*14*). Precipitation data were synthesized using a Thiessen weighting approach to obtain a value for the watershed. The number of reporting stations differed with time ranging from a minimum of ~450 in the early 1900s to a maximum of ~1250 in the 1950s with good areal coverage throughout the period of record. Runoff was estimated using streamflow records from major rivers, available from the U.S. Geological Survey for U.S. streams and the Inland Waters Directorate of Environment Canada for Canadian streams. Evaporation was estimated using a lumped-parameter surface flux and heat-storage model. Estimates are based on measurements of areal-average daily air temperature, windspeed, humidity, precipitation, and cloudcover. Detailed descriptions of computation methods and the data used are available in

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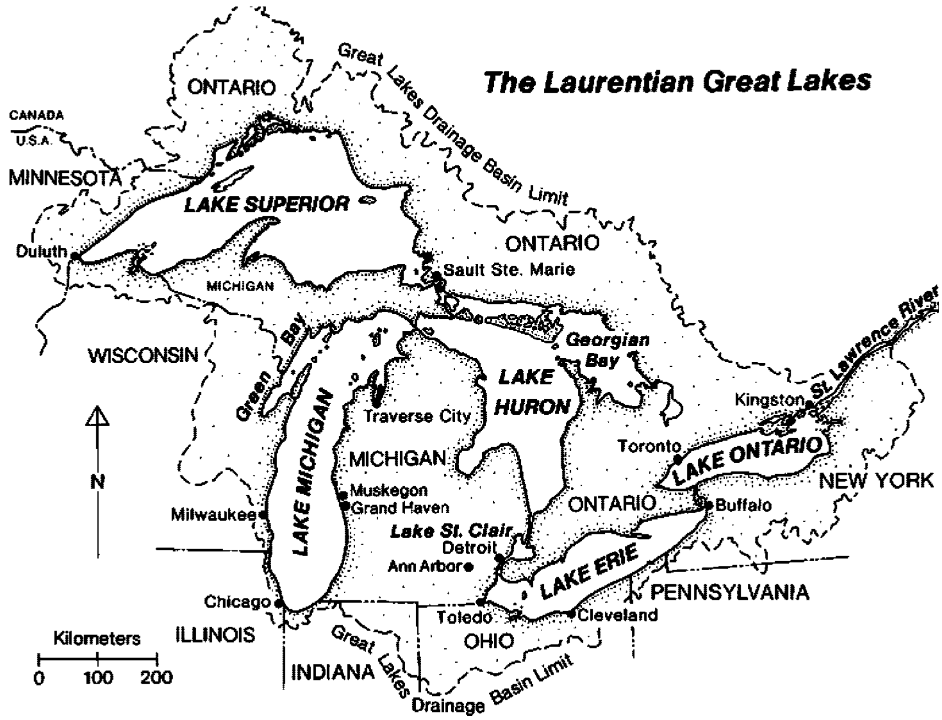

FIGURE 1. Laurentian Great Lakes and drainage basin.

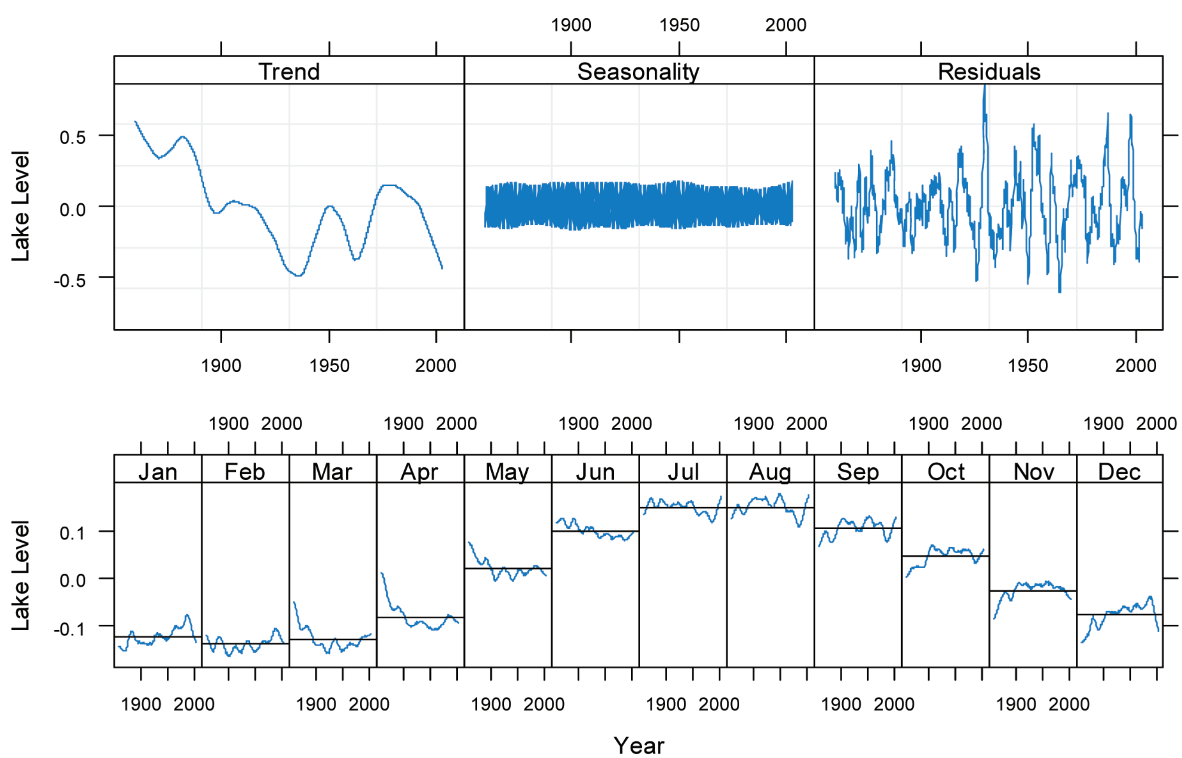

FIGURE 2. STL results depicting the long-term water level component (top left), seasonal component (top center), and residuals (top right). Bottom panel depicts monthly trends from 1860 to 2006, solid horizontal line is the long-term mean for each month. Figures are centered on long-term mean water level.

Croley and Hunter (*14*) and Assel et al. (*15*). Sunspot data (1900−2005) were obtained from NOAA's National Geophysical Data Center's online database (*16*).

Seasonal Trend Decomposition Using Loess (STL). To evaluate overall patterns for the entire water level series (1860–2006) we used a graphically based approach: Seasonal Trend decomposition using loess (local error sum of squares) or STL (*17, 18*). STL is an iterative nonparametric procedure using repeated loess fitting. A time-series of monthly monitoring data may be considered as a sum of three components: one high-frequency seasonal component, one low-frequency long-term component (or trend), and a residual component:

$$Y_{\text{year,month}} = T_{\text{year,month}} + S_{\text{year,month}} + R_{\text{year,month}} \quad (1)$$

where $Y_{\text{year,month}}$ is the observed value for a given year and month, $T_{\text{year, month}}$ is the trend component, $S_{\text{year, month}}$ is the

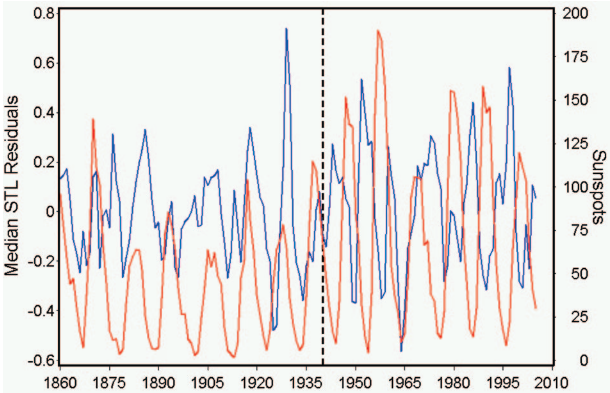

FIGURE 3. Median annual STL residual (blue) and annual sunspot number (red) vs time. Vertical dashed line at 1940 indicates approximate time of reversal in the relationship.

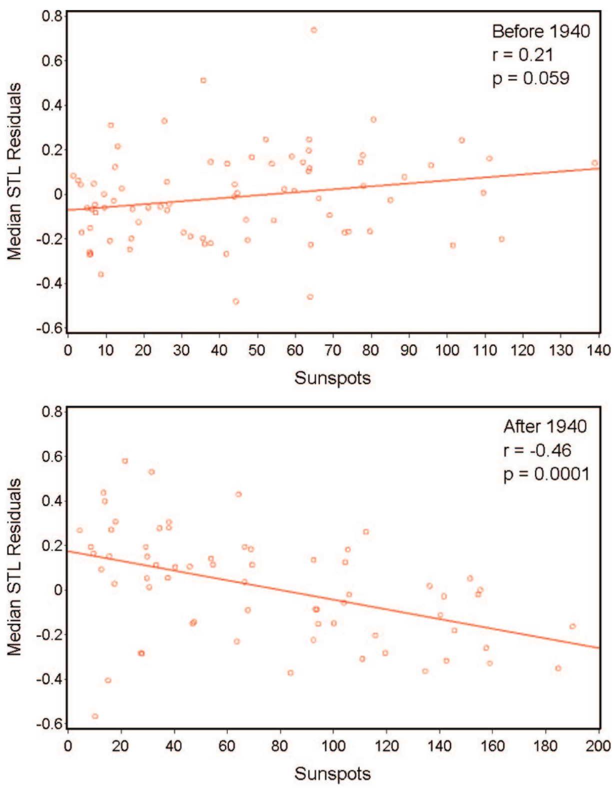

FIGURE 4. Bivariate relationship between median STL residuals and sunspot number before (top) and after (bottom) 1940.

seasonal component, and $R_{\mathrm{year,month}}$ is the residual term. STL uses one continuous loess line for the long-term trend component and 12 month-specific loess lines for the seasonal component. Fitting is done on each component iteratively until the resulting trend and seasonal components stabilize. The nonparametric nature of STL makes it flexible in revealing nonlinear patterns in seasonal data. Because each month is a subseries in the fitted loess model the seasonal pattern can evolve with time revealing changes in timing, amplitude, and variance that occur in the seasonal cycle.

Dynamic Linear Models (DLMs). We examined the relationship between annual average lake level and several candidate predictor variables: precipitation (1900–2004), and temperature and evaporation (1948–2005), using BATS (Bayesian Analysis of Time Series) software to estimate Dynamic Linear Models (DLMs) (*19*). DLMs partition variation in the response variable into a trend component, regression components that describe the relationship with

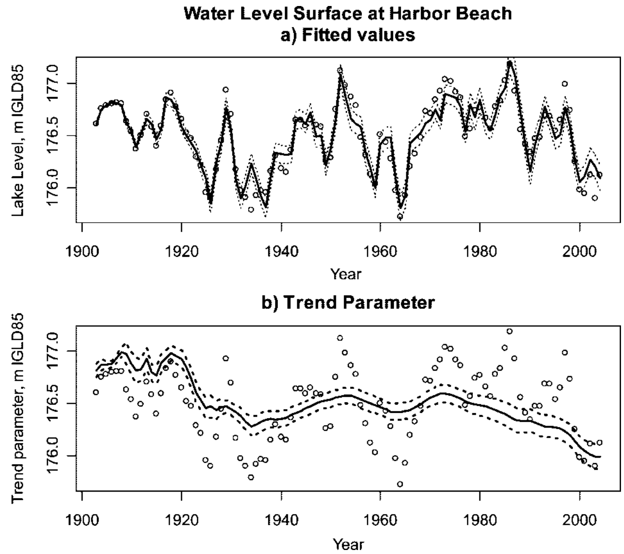

FIGURE 5. Best fit DLM for Lake Michigan surface level, using a constant trend and Lag 1, Lag 2, and Lag 3 years of precipitation: (a) fitted values, and (b) smoothed trend parameter. Open circles represent mean annual observed values, solid lines represent mean fitted values and trend parameter estimates, and dotted lines represent a 90% credible interval about the mean fitted values and mean trend parameter, respectively.

predictor variables, and random components (*20, 21*). DLMs are similar to linear regression models, however, DLMs allow model coefficients to change with time whereas linear regression models are based on the assumption of a static relationship. Older information is discounted by adding uncertainty with the passage of time, recognizing that newer information is more valuable for forecasting. The discount factor is δ which is equal to 1 λ, where λ is the discount *rate*. For a discount factor δ between 0 and 1, the information loss for each time interval is $V_t = \delta^{-1}V_{t-1}$, such that for a 5% information loss, δ is about 0.95 (*19*). Useful discounts are typically >0.8; smaller discounts lead to models that make predictions based on only the 2 or 3 most recent observations (*20*). Model selection is based on forecast performance; BATS provides the cumulative log likelihood, median absolute deviation, and mean squared error for each model tested.

So that model comparisons would be based on the same amount of data we estimated DLMs using truncated data (1903–2004) providing up to three annual precipitation lags. We first investigated two different specifications of the trend component. In the constant trend model, the trend parameter at time t is a discounted version of the trend parameter at time $t-1$. In the linear trend model, the trend consists of two parameters at time t, a constant as well as an annual rate of change, which are discounted versions of the constant and rate at time $t-1$. With a fixed time increment, the growth parameter may be interpreted as a linear slope, therefore this is known as a linear trend or linear growth model. Then, based on exploratory analyses we investigated precipitation with up to three annual lags, and also considered the addition of temperature, and evaporation in various combinations for the shorter period of record (1948–2005) that these measurements were available. Subsequently, based on the results of the STL analysis, we evaluated the addition of sunspot index as a predictor for the period of record from 1903 to 2004. All candidate predictor variables were transformed by centering about their mean values to facilitate plotting the results. The last components evaluated in these models were discount rates associated with the trend and regression coefficients (*20, 21*). To provide a familiar statistic

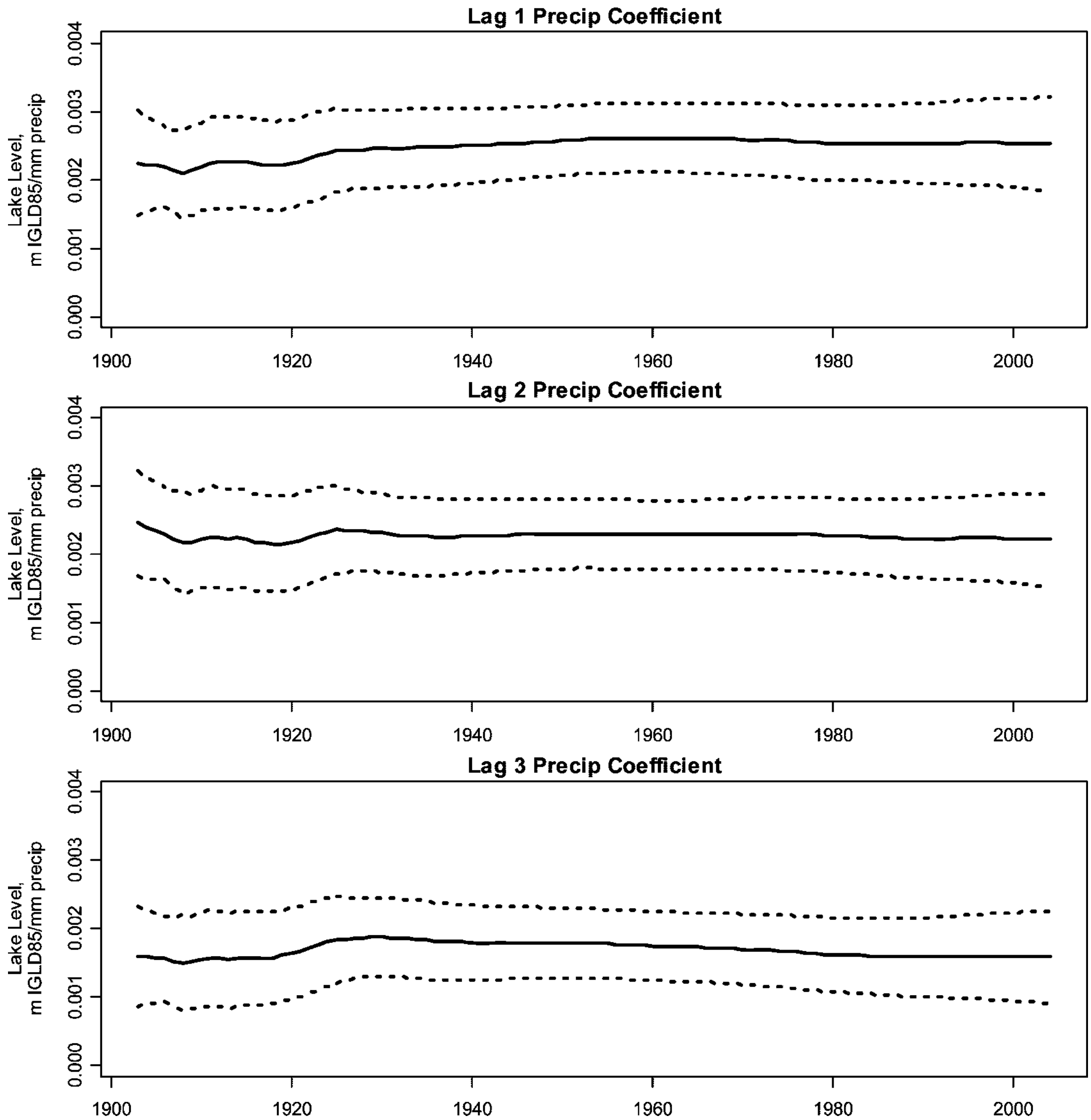

FIGURE 6. Smoothed regression coefficients from the DLM providing the best fit for Lake Michigan surface elevation, using the three lagged precipitation predictors. Dotted lines represent a 90% credible interval about the mean coefficient values.

for model evaluation we calculated an approximate R^2 for the final model as $1 - \Sigma(y_i - \hat{y}_i)^2/\Sigma(y_i - \bar{y})^2$, where y_i = observed lake level, $\hat{y}$ = mean predicted lake level, and $\bar{y}$ = average observed lake level.

Hydrologic Continuity Equation Method. Great Lakes water levels are driven by the hydrologic cycle and quantified by the hydrologic continuity equation where units are expressed in millimeters over the lake area:

$$\Delta S = P + R \pm G - E - O + I \qquad (2)$$

where ΔS = change in storage (lake level change), P = precipitation, R = surface runoff, G = groundwater flow, E = evaporation, I = inflows from the St. Marys river (upstream), and O = outflows through the St. Clair River (downstream).

Assuming negligible groundwater inputs and evaluating only the atmospheric inputs and outputs, ΔS is then estimated using P, R, and E. Although not explicitly shown in eq 2, air temperature plays a major role in lake levels as it factors into lake evaporation. Because the length of record for runoff was a limiting factor (1948–2003), this period of record was used to compute the change in storage.

Results

STL Results. STL decomposes a time series into three components: a smoothed long-term trend (Figure 2 top left), a seasonal cycle of varying amplitude (Figure 2 top center), and residuals (Figure 2 top right). The long-term trend line indicates a sustained lake-level decline occurring before 1900 and a longer-term oscillation with an irregular visual periodicity of ~30 years. This component also highlights the recent decline with lake levels in 2006 near record lows.

With seasonality depicted monthly (Figure 2 bottom) we see that the overall pre-1900 decline was accentuated in the spring, indicated by a declining seasonal component in March–June, and dampened in the autumn–early winter, indicated by increasing October–December components. Recently, the summer months June–August show small increases, while winter months November–February show decreases, indicating a slight recent increase in the seasonal fluctuation range (Figure 2 top center).

Visually, the residuals (Figure 2 top right) suggest a remnant oscillation with a periodicity of ~11–13 years, approximately that of the sunspot cycle. When residuals and sunspots are plotted together, the peaks and troughs appear approximately consistent before 1940, with a near reversal of this pattern after ~1940 (Figure 3). Bivariate plots of STL residuals vs sunspots before and after 1940 confirm a weak positive relationship in the earlier period and a pronounced negative relationship in the latter period (Figure 4).

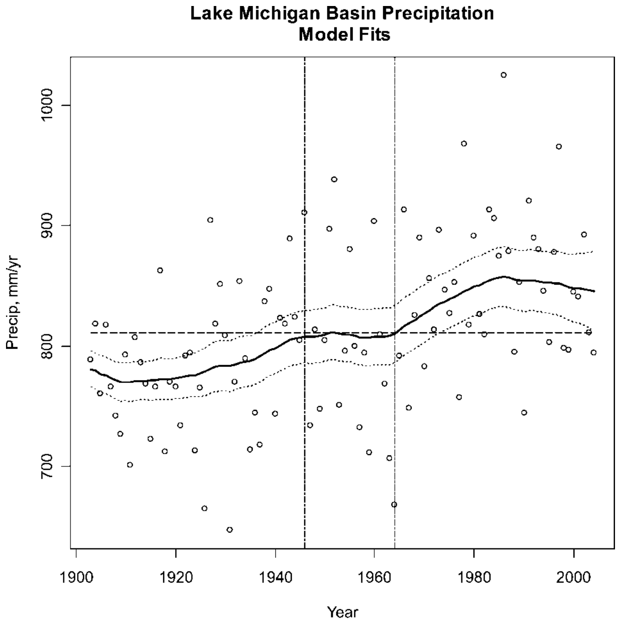

FIGURE 7. Fitted values for the DLM providing the best fit for Lake Michigan basinwide precipitation. Open circles represent mean annual observed values, solid lines represent mean fitted values, and dotted lines represent a 90% credible interval about the fitted values. Horizontal dashed line indicates the mean annual precipitation for the period of record. Vertical dash-dot lines highlight slope changes.

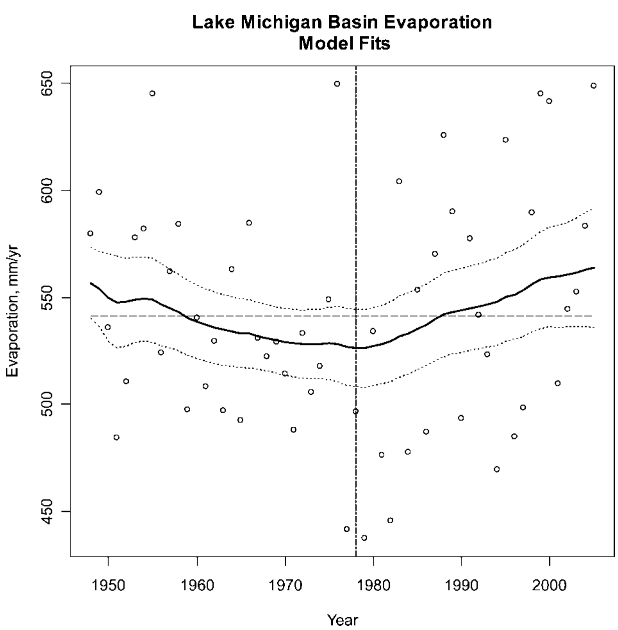

FIGURE 8. Fitted values for a DLM providing the best fit for Lake Michigan basin-wide evaporation. Open circles represent mean annual observed values, solid lines represent mean fitted values, and dotted lines represent a 90% credible interval about the fitted values. Horizontal dashed line indicates the mean annual evaporation for the period of record. Vertical dash-dot lines highlight slope changes.

DLM Results. Using default values for the model discounts, the best model included a constant trend with one, two, and three year lags of precipitation. Using this model we then relaxed the discounts and, based on comparisons of the log integrated likelihoods (Bayes factors), the resultant best model included a trend discount of 0.80 with (default) regression coefficient discounts of 0.98.

The resultant model, with three annual precipitation lags, captures historical lake level variation rather well (approximate $R^2 = 0.89$; Figure 5 top) and exhibits a rapid decline beginning ~1920, with a steady underlying decline in the trend component beginning in the late 1970s continuing through 2005 (Figure 5 bottom). The three precipitation coefficients show little change with time (Figure 6), indicating that lake level responses to precipitation have been fairly consistent.

Precipitation, itself, exhibits a general increasing trend from 1900 until the late 1980s and has been flat or slightly declining since (Figure 7). Although the experimental addition of temperature and evaporation over the shorter time period for which these data were available did not appreciably improve the model fit statistics, a separate DLM analysis of the evaporation data indicates a clear change in evaporation trends, shifting from a negative to a positive pattern in ~1978 (Figure 8).

Experimentally including sunspots in the model with three precipitation lags did not improve the model fit either, or alter the estimated precipitation coefficients appreciably, but the sunspot coefficient estimated using DLM corroborates STL residual results (Figures 3 and 4), indicating a weak positive relationship early in the series, crossing the axis in ~1940 and becoming increasingly negative (Supporting Information).

Hydrologic Continuity Equation Results. Each hydrologic component was evaluated initially by computing a linear regression for its overall period of record. When evaluating evaporation, it was noted that although there was an overall increase in evaporation, there was a clear difference in rates of change for specific periods. For example, for the period 1948−1977, evaporation showed a decreasing rate of change; and, for the period 1978−2005, evaporation showed a clear increasing rate (Figure 8). Given the shifts in trends for evaporation, all components and change in storage were evaluated based on the above two time periods for a change in trend. Figure 9 shows that components which would contribute to lake level rise such as precipitation and runoff showed either a change in rates such as increasing to decreasing as in the case of precipitation or a lessening in the rate of increase as in runoff. Similarly, the factor that contributes to a decrease in lake levels, evaporation, showed a clear switch in its linear trend. Thus, the lessening and/or total reversal in the rate of change in these individual components resulted in a decreasing change in storage; from 3.9 mm/yr to −3.12 mm/year.

Discussion

Relationships between lake level and sunspots have been observed in various lakes worldwide. The reported associations have differed among lakes (*22–27*), have sometimes been disputed, and occasionally reversals in the sign of the relationship have been noted (*28–32*). Similarly, documented relationships between the solar cycle and lake level causal factors, such as rainfall, have differed with positive and negative relationships reported (*33–35*).

In the Great Lakes, Hubbard (*36*) reported a correspondence between sunspot maxima, rainfall minima, and lower lake levels in Lake Erie (1834–1886) with a lag of ~3 years. Nassau and Koski (*37*) indicated a varying relationship in Lake Erie from 1860 to 1925. Brunt (*30*) reported that Lake Michigan levels "…show maxima fairly closely in agreement with the times of the last three sunspot maxima" (referring to 1907, 1917, and 1928) but "they show little agreement with earlier maxima." Subsequently, Wilson (*38*) reported a positive relationship in Lake Michigan from 1860 to 1942 with a mean lag of ~1 year. Our results, indicating a weak positive relationship in the pre-1940 period are consistent

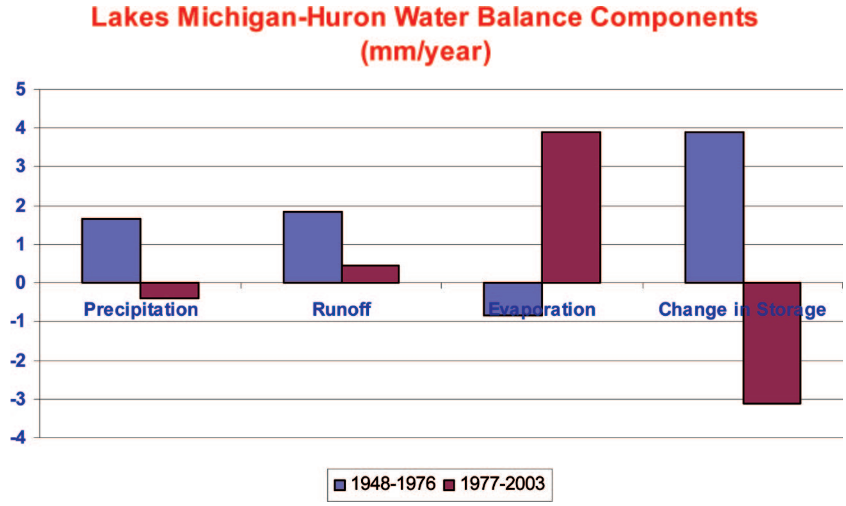

FIGURE 9. Lakes Michigan−Huron water balance component changes with time.

with these earlier reports, though we did not attempt to maximize this relationship by experimenting with lagged data. The timing of the switch from a positive to negative correlation is coincident with what has been previously identified as a change from a drier to a wetter regional climate (*12*). While this reversal is similar to what Stager et al. (*32*) report we could not discern a relationship between sunspots and either precipitation or evaporation that would support a causal link. Though the sunspot relationship reflects only a small component of annual lake level variance, clarifying the factors responsible for these differing and time-varying relationships may be useful to refine future climate-change lake level assessments.

Our STL results, through 2006, highlight a recent increase in seasonal lake level variability. Lenters (*39*) used a different approach to look at seasonal changes and concluded that changes were occurring Jan−April and Nov−Dec, roughly consistent with our results. However, Quinn (*40*) examined seasonal water level range through 2000 and concluded that we were in a period of possibly sustained low seasonal fluctuation. Similarly, analyzing data through 1995, Argyilan and Forman (*41*) proposed a dampening of the seasonal cycle resulting from decreases in spring runoff and increases in autumn−winter runoff. These somewhat differing interpretations, arising in a relatively short interval, underscore the conclusion that these lakes are changing rapidly at both annual and multiple-year time scales.

On a multidecadal scale, the STL results depict 5 peaks over the 146 year period of record (Figure 2 top left), consistent with the ∼30 year synoptic periodicity reported by Polderman and Pryor (*42*). Both the STL and DLM suggest a relatively stable period in the mid 1900s, which has been followed by a decline that began in the late 1970s. This decline may have been masked by concurrent increasing precipitation. Our water balance analysis suggests that the decline results largely from increasing evaporation; we speculate that the signal was difficult to discern with the DLM because of its reversal and relatively short period of record.

Based on the ∼30 year periodicity revealed by the STL results (Figure 2), it is tempting to speculate that lake levels will soon return to previous norms. However, the high levels experienced in the 1980s demonstrated that future fluctuations may differ from fluctuations of the recent past (*43*). We cannot be sure that the present observed decline portends a long-term problem, but the credible intervals about the trend line (Figure 5) offer at least 20:1 odds that the current trend parameter value is the lowest on record. Although observed water levels did not begin declining until 1998, the underlying decline has been ongoing since ∼1973. Prior to 1998 the underlying decline was probably obscured by concurrent precipitation increases (Figure 7).

DLM forecasts indicate that, at the long-term average precipitation rate of ∼811 mm, the lakes will attain an annual average level of 176.0 m in 2010 (90% credible interval = 175.7–176.3 m), approximately 0.65 m below the long-term average level. A more optimistic scenario, using the long-term average precipitation + 1 standard deviation (811 mm + 70 mm) predicts a level by 2010 of 176.3 m (90% credible interval of 176.0–176.6 m). These model forecasts, with accompanying uncertainty estimates, offer testable hypotheses that can be evaluated and updated with accumulating data. However, they suggest that an extended period of relatively high precipitation may be required for lake levels to recover from the drop that became apparent in the late 1990s (*1*).

Acknowledgments

This manuscript is GLERL contribution number 1449.

Supporting Information Available

Figure showing precipitation and sunspot coefficients resulting from a DLM with three lags of precipitation and sunspot number included in the model. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Assel, R. A.; Quinn, F. H.; Sellinger, C. E. Hydroclimatic factors of the recent record drop in Laurentian Great Lakes water levels. *Bull. Am. Meteorol. Soc.* **2004**, *85*, 1143–1151.

(2) Meadows, G. A.; Meadows, L. A.; Wood, W. L.; Hubertz, J. M.; Perlin, M. The relationship between Great Lakes water levels, wave energies, and shoreline damage. *Bull. Am. Meteorol. Soc.* **1997**, *78*, 675–683.

(3) Baedke, S. J.; Thompson, T. A. A 4700-year record of lake level and isostasy for Lake Michigan. *J. Great Lakes Res.* **2000**, *26*, 416–426.

(4) Larsen, C. Reconstructing Holocene lake level fluctuations in the Lake Superior Basin. In Sellinger, C. E., Quinn F. H., Eds.; *Proceedings of the Great Lakes Paleo-Levels Workshop: The Last 4000 Years*;NOAA Technical Memorandum ERL-GLERL-113; 1999.

(5) Croley, T. E. Laurentian Great-Lakes double-CO_2 climate change hydrological impacts. *Clim. Change* **1990**, *17*, 27–47.

(6) Smith, J. B. The potential impacts of climate change on the Great-Lakes. *Bull. Am. Meteorol. Soc.* **1991**, *72*, 21–28.

(7) Magnuson, J. J.; Webster, K. E.; Assel, R. A.; Bowser, C. J.; Dillon, P. J.; Eaton, J. G.; Evans, H. E.; Fee, E. J.; Hall, R. I.; Mortsch, L. R.; Schindler, D. W.; Quinn, F. H. Potential effects of climate changes on aquatic systems: Laurentian Great Lakes and Precambrian Shield Region. *Hydrol. Processes* **1997**, *11*, 825–871.

(8) Lofgren, B. M.; Quinn, F. H.; Clites, A. H.; Assel, R. A.; Eberhardt, A. J.; Luukkonen, C. L. Evaluation of potential impacts on Great Lakes water resources based on climate scenarios of two GCMs. *J. Great Lakes Res.* **2002**, *28*, 537–554.

(9) Schwartz, R. C.; Deadman, P. J.; Scott, D. J.; Mortsch, L. D. Modeling the impacts of water level changes on a Great Lakes community. *J. Am. Water Resour. Assoc.* **2004**, *40*, 647–662.

(10) Lake Carriers' Association. Suite 915, 614 West Superior Avenue, Cleveland, OH 44113. www.lcaships.com.

(11) Hecky, R. E.; Smith, R. E. H.; Barton, D. R.; Guildford, S. J.; Taylor, W. D.; Charlton, M. N.; Howell, T. The nearshore phosphorus shunt: a consequence of ecosystem engineering by dreissenids in the Laurentian Great Lakes. *Can. J. Fish. Aquat. Sci.* **2004**, *61*, 1285–1293.

(12) Changnon, S. A. Temporal behavior of levels of the Great Lakes and climate variability. *J. Great Lakes Res.* **2004**, *30*, 184–200.

(13) NOAA Tides and Currents Data Base. National Oceanic and Atmospheric Administration, National Ocean Service, 2006; http://tidesandcurrents.noaa.gov/station_retrieve.shtml?type=Historic+Great+Lakes+Water+Level+Data/.

(14) Croley, T. E., II; Hunter, T. S. *Great Lakes Monthly Hydrologic Data*; NOAA Technical Memorandum ERL GLERL-83, Great Lakes Environmental Research Laboratory: Ann Arbor,MI (NTIS# PB95-173076/XAB); 1994; 83 pp.

(15) Assel, R. A.; Sellinger, C. E.; Meyer, D. E.; Kelly, R. N. *Great Lakes States Monthly Precipitation Data- Beginning of Record to 1990*; NOAA Technical Memorandum ERL GLERL-89; Great Lakes Environmental Research Laboratory: Ann Arbor, MI, 1995.

(16) NOAA National Geophysical Data Center. Solar Data Services. http://www.ngdc.noaa.gov/stp/SOLAR/ftpsunspotnumber.html, 2006.

(17) Cleveland, W. S. *Visualizing Data*; Hobart Press: Summit, NJ, 1993.

(18) Qian, S. S.; Borsuk, M. E.; Stow, C. A. Seasonal and long-term nutrient trend decomposition along a spatial gradient in the Neuse River watershed. *Environ. Sci. Technol.* **2000**, *34*, 4474–4482.

(19) Pole, A.; West, M.; Harrison, J. *Applied Bayesian Forecasting and Time Series Analysis* **1994**, *2*, 3:13–37.

(20) West, M.; Harrison, P. J. *Bayesian Forecasting and Dynamic Models*; Springer-Verlag: New York, 1989.

(21) Lamon, E. C.; Carpenter, S. R.; Stow, C. A. Forecasting PCB concentrations in Lake Michigan salmonids: A dymanic linear model approach. *Ecol. Appl.* **1998**, *8*, 559–668.

(22) Dixey, F. Lake level in relation to rainfall and sunspots. *Nature* **1924**, *114*, 659–661.

(23) Bowman, I. Correlation of sedimentary and climatic records. *Proc. Natl. Acad. Sci.* **1933**, *19*, 376–388.

(24) Cohen, Y.; Radomski, P. Water-level regulations and fisheries in Rainy Lake and the Namakan Reservoir. *Can. J. Fish. Aquat. Sci.* **1993**, *50*, 1934–1945.

(25) Hallett, D. J.; Mathewes, R. W.; Walker, R. C. A 1000-year record of forest fire, drought and lake-level change in southeastern British Columbia, Canada. *Holocene* **2003**, *13*, 751–761.

(26) Kadioglu, M.; Sen, Z.; Batur, E. The greatest soda-water lake in the world and how it is influenced by climatic change. *Ann. Geophys.-Atmos. Hydro. Space Sci.* **1997**, *15*, 1489–1497.

(27) Sen, Z.; Kadioglu, M.; Batur, E. Stochastic modeling of the Van Lake monthly level fluctuations in Turkey. *Theor. Appl. Climatol.* **2000**, *65*, 99–110.

(28) Brooks, C. E. P. Variations in the levels of central African Lakes Victoria and Albert. *Geophys. Mem., London* **1923**, *20*, 337–344.

(29) Henry, A. J.; Brooks, C. E. P. On variations in the level of the central African Lakes, Victoria and Albert. *Monthly Weather Rev.* **1924**, *52*, 148–152.

(30) Brunt, D. Climatic cycles. *Geograph. J.* **1937**, *89*, 214–230.

(31) Kanthack, F. E. The fluctuations of Lake Nyasa. *Geograph. J.* **1941**, *98*, 20–33.

(32) Stager, J. C.; Ryves, D.; Cumming, B. F.; Meeker, L. D.; Beer, J. Solar variability and the levels of Lake Victoria, East Africa, during the last millennium. *J. Paleolimnol.* **2005**, *33*, 243–251.

(33) Verschuren, D.; Laird, K. R.; Cumming, B. R. Rainfall and drought in equatorial east Africa during the past 1,100 years. *Nature* **2000**, *403*, 410–414.

(34) Thresher, R. E. Solar correlates of Southern Hemisphere mid-latitude climate variability. *Int. J. Climatol.* **2002**, *22*, 901–915.

(35) Tsiropoula, G. Signatures of solar activity variability in meteorological parameters. *J. Atmos. Solar-Terrestr. Phys.* **2003**, *65*, 469–482.

(36) Hubbard, B. *Memorials of a Half Century*; G.P Putnam's Sons: New York, 1887.

(37) Nassau, J. J.; Koski, W. Lake Erie levels and sun-spots. *Pop. Astron.* **1933**, *41*, 198–201.

(38) Wilson, B. H. Some deductions made from a correlation of Lake Michigan water levels with the sun-spot cycles. *Pop. Astron.* **1946**, *54*, 73–84.

(39) Lenters, J. D. Long-term trends in the seasonal cycle of Great Lakes water levels. *J. Great Lakes Res.* **2001**, *27*, 342–353.

(40) Quinn, F. H. Secular changes in Great Lakes water level seasonal cycles. *J. Great Lakes Res.* **2002**, *28*, 451–465.

(41) Argyilan, E. P.; Forman, S. L. Lake level response to seasonal climatic variability in the Lake Michigan-Huron system from 1920 to 1995. *J. Great Lakes Res.* **2003**, *29*, 488–500.

(42) Polderman, N. J.; Pryor, S. C. Linking synoptic-scale climate phenomena to lake-level variability in the Lake Michigan-Huron basin. *J. Great Lakes Res.* **2004**, *30*, 419–434.

(43) Keillor, J. P. Planning for a wider range of water levels along Great-Lakes and ocean coasts. *Coastal Manage.* **1990**, *18*, 91–103.

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